Radiation Damage and Waste Management Options for the SOMBRERO Final Focus System and Neutron Dumps*

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Abstract

Previous studies of the safety and environmental aspects of the SOMBRERO inertial fusion energy (IFE) power plant design did not completely address the issues associated with the final focus system. While past work calculated neutron fluences for a grazing incidence metal mirror (GIMM) and a final focus mirror, scattering off of the final optical component was not included, and thus, fluences in the final focus mirror were significantly understimated. In addition, past work did not consider neutron-induced gamma-rays. Finally, power plant lifetime waste volumes may have been underestimated as neutron activation of the neutron dumps and building structure were not addressed. In the present work, a modified version of the SOMBRERO target building is presented where a significantly larger open solid-angle fraction (5%) is used to enhance beam smoothing of a diode-pumped solid-state laser (DPSSL). The GIMMs are replaced with transmissive fused silica wedges and have been included in three-dimensional neutron and photon transport calculations. This work shows that a power plant with a large open solid-angle fraction is acceptable from tritium breeding and neutron activation points-of-view.

Introduction/Description of the problem

- The SOMBRERO IFE power plant design has been modified to enable a DPSSL driver.[1]

- The open solid-angle fraction has been increased from 0.25% to 5%, and the GIMMs have been replaced by transmissive wedges for the final optic component.

Feature	KrF-SOMBRERO	DPSSL-SOMBRERO
Total open solid-angle fraction	0.25%	5%
Number of beams	60	60
Open solid-angle fraction per beam	4.17E-05	8.33E-04
Half-angle of each beam	0.74 degrees	3.31 degrees
Penetration radius at the first wall	8.4 cm	37.6 cm
Line-of-sight radius at the final optical element	38.7 cm	173.4 cm
Line-of-sight radius at the neutron dump	64.6 cm	289.0 cm
Thickness of the wall of the neutron dump	50 cm	50 cm
Depth of the neutron dump	193.8 cm	500 cm
Required deflection angle to miss the neutron dump	4.85 degrees	17.04 degrees
Deflection angle of the final optical element	GIMM = 6.0 degrees	Wedge = 34.08 degrees

- Larger neutron dumps are needed to protect the final focusing mirrors, and thus the bending angle of the wedge must be increased.

- Design minimizes the thickness of the wedges in two ways:
  - Splitting each beam in two so that two final focusing mirror arrays send their respective beams to a single array of wedges
  - Use of rectangular/elongated configuration for the beams as opposed to the square configuration

$q_1 = 17.04^o$ $q_2 = 11.53^o$ $q_3 = 6.77^o$
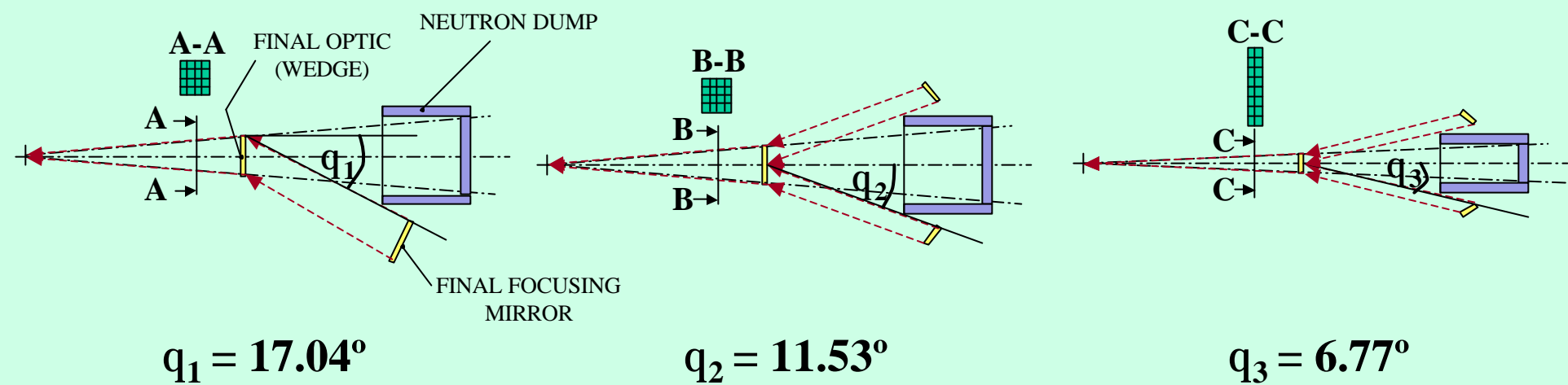
The wedge bending angle can be reduced from the baseline value of 17.04° to 11.53° by switching to two final focus mirrors. By using a rectangular beam configuration instead of a square one, the bending angle can be further reduced to 6.77°.

Overview of SOMBRERO KrF-driven design

- Significant findings after reviewing the previous work completed for the KrF SOMBRERO:
  - Neutron-induced gamma-ray doses in the optics were not considered (recent work in support of NIF indicates it can be of great importance when estimating the lifetime of optical components)[2]
  - GIMM was not modeled (neutron scattering from this element is important)
  - 1-D scaling was used to calculate the fast neutron flux at the final focusing mirror position
  - Estimates of optics lifetimes were made assuming a range of neutron fluence limits

Both neutron and gamma-ray doses must be considered to calculate lifetimes of the optical elements. 3-D modeling for the neutronics calculations is essential in order to account for neutron scattering. A complete analysis requires more material data about the fast neutron and gamma-ray fluence limits.

Computational methods

- TART98 Monte Carlo neutron and photon transport code has been used for neutronics calculations.[3]

- A 3-D model of 1/8 of the total geometry with 3 reflecting planes and a point neutron source at the origin emitting neutrons isotropically with the SOMBRERO target energy spectrum were used.

- Neutron activation calculations have been performed using the ACAB radionuclide generation/depletion code.[4]

- The FENDL/A-2.0 activation cross-section library has been used.[5]

- Typical impurities have been considered in the SiO_2 used for wedges and mirrors substrate.[6] Two different materials have been considered for the dielectric coating of the mirrors: ZnS and MgF_2.
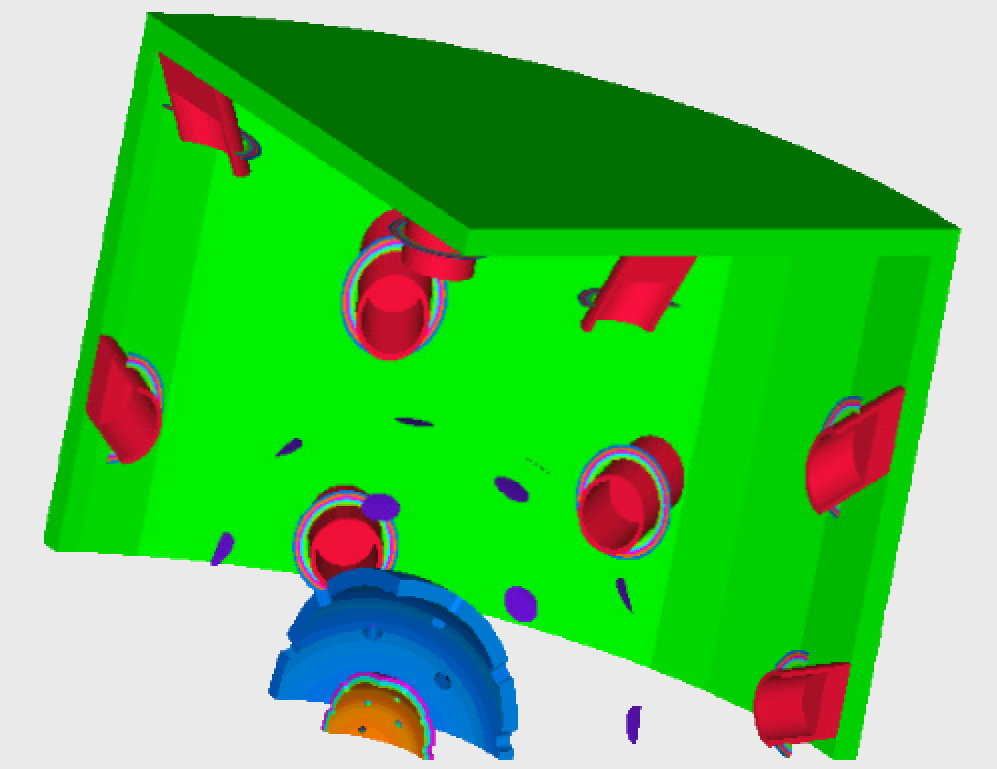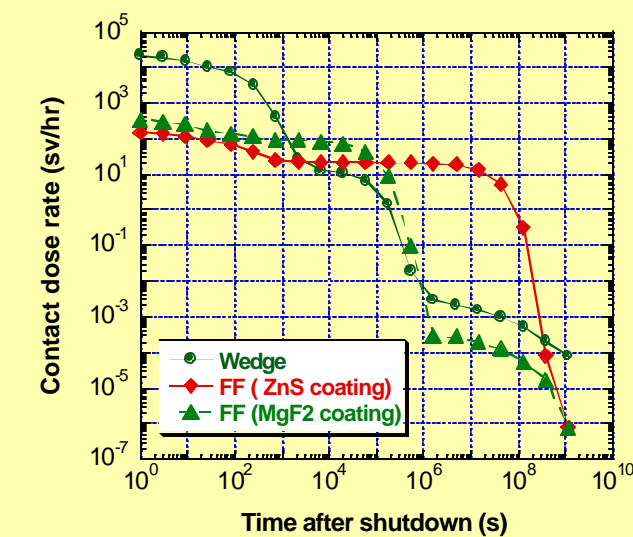

The 3-D model includes the detailed radial build of the SOMBRERO design at the midplane for the blanket/reflector, the inner shield and the reactor building. The wedges are 30 m from the target and a baseline thickness of 3 cm was used. Neutron dumps help protect the final focusing mirrors. Dose rates and fluxes at the final focusing mirror position have been obtained in cylindrical rings around the neutron dumps.

Results on radiation damage and waste management

- Tritium breeding ratio with 5% open solid angle is 1.16.

- At the wedge, the fast neutron and gamma fluxes are 9.54×10^{12} n/cm^2s and 4.55×10^{12} γ/cm^2s. Dose rates are 110 Gy/s and 36 Gy/s for fast neutrons and gamma-rays, respectively.

- Dose rates and fluxes at the final focusing mirror are shown in the figure below as a function of the distance to the line-of-sight axis:
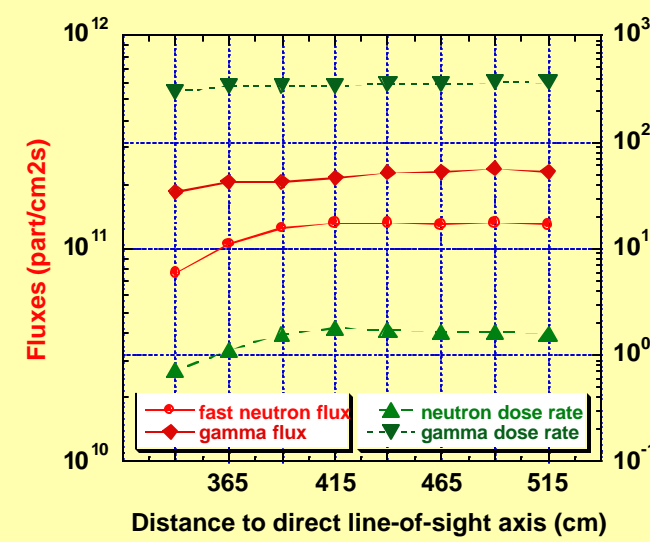
Particles that scatter off of the wedges dominate these fluxes, so these results scale with the open solid-angle fraction and the wedge thickness.

- For a range of fluence limits from 10^{20} to 10^{22} n/cm^2 the results for the wedges show that:
  - Lifetime of the wedges would be 0.33 to 33 FPY
  - WDR would range from 9.2×10^{-5} to 1.5×10^{-2}
  - Volume of waste after 30 years operation from 17 to 1600 m^3
  - Results are conservative given that the wedges are expected to be self-annealing[7]

- For the final focusing mirrors, results have been obtained for a range of fluence limits from 10^{18} to 10^{19} n/cm^2:
  - Lifetime from 0.25 to 2.5 FPY
  - Waste volume from 270 to 2700 m^3
  - WDR for SiO_2 substrate and dielectric coating less than 10^{-5}

- Contact dose rates for the optics have been obtained conservatively assuming the longer lifetimes:

Wedges and final focusing mirrors require remote recycling. MgF_2 is recommended as dielectric coating material as it gives lower values of WDR and contact dose rate.

- Results for the concrete building shell and neutron dumps meet waste disposal rating criterion WDR < 1:

Open solid angle	neutron dumps	building
0.25%	4.39E-1	4.86E-4
5%	4.72E-1	1.20E-2

- Contact dose rates have been obtained for the building shell and neutron dumps:
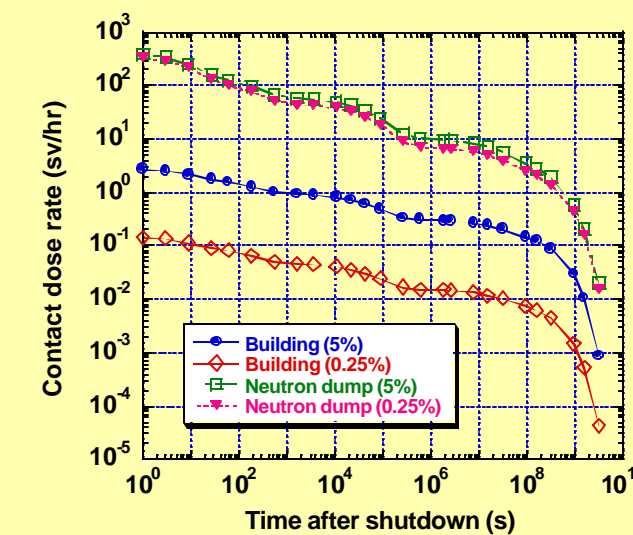
The contact dose rate of the neutron dumps is significantly higher than that of the building shell. The neutron dump dose rate is independent of the solid-angle fraction, but the results for the building shell vary linearly with the solid angle.

Conclusions and Recommendations

- In order to make SOMBRERO design suitable for an inertial fusion power plant using a DPSSL driver, the open solid-angle fraction may need to be increased to provide additional bandwidth, and thus, more beam smoothing.

- The fast neutron flux at the final focusing mirror position (located near the outer building wall at 45 m from target) is dominated by neutrons scattered by the wedges (used to bend the beam, located at 30 m from target), so it is proportional to the open solid-angle fraction as well as the thickness of the wedges.

- Smaller values of the open solid-angle fraction will translate directly into longer lifetime of the final focusing mirrors. This can be achieved through an increase in the laser bandwidth; the value of 5% is believed to be an upper limit.

- Contact dose rates and waste management for neutron dumps are rather insensitive to the open-solid angle fraction.

- More experimental data are essential on radiation damage to optical materials. R&D on radiation-hardened coatings and recycling techniques for these components is needed.

References

[1] OSIRIS and SOMBRERO Inertial Fusion Power Plant Designs, WJSA-92-01, DOE/ER/54100-1.
[2] C. D. Marshall, J. A. Speth, S. A. Payne, Induced optical absorption in gamma, neutron and ultraviolet irradiated fused quartz and silica, J. of Non-Crystalline Solids 212 (1997) 59-73.
[3] D. E. Cullen, "TART98: A Coupled Neutron Photon, 3-D, Combinatorial Geometry, Time Dependent, Monte Carlo Transport Code", LLNL, UCRL-ID-126455, Rev. 2 (1998).
[4] J. Sanz, "ACAB98: Activation code for fusion applications. User's Manual V4.0", Universidad Nacional de Educacion a Distancia (UNED), LLNL, UCRL-CR-133040 (1999).
[5] A.B Pashchenko, H. Wienke, J. Kopecky, J.-Ch Sublet, R.A. Forrest, "FENDL/A-2.0 Neutron Activation Cross-Section Data Library for Fusion Applications", International Atomic Energy Agency, IAEA-NDS-173 (Mar. 1997).
[6] T. G. Parham, personal communication (Aug. 1999).
[7] C. D. Orth, S. A. Payne, W. F. Krupke, A diode pumped solid state laser driver for inertial fusion energy, Nucl. Fus. 36 (1996) 75-116.